Application to Radio of Wire Transmission Engineering[1]

By LLOYD ESPENSCHIED

SYNOPSIS: This article points out that radio and wire communication systems are subject, fundamentally, to the same general requirements, and its purpose is to develop for radio, points of view which are familiar to wire transmission engineers. The transmission characteristics over a wide range of distances are compared. For short distances the comparison is favorable to wires. Although over great distances, the attenuation of electric waves, guided by wires, may be greater than the unguided waves of radio, it is pointed out that at the present time intermediate amplifiers can be more economically applied in wire transmission than in radio to boost the message energy. Economy of transmission requires the handling of messages at as low an energy level as possible and, as the author points out, wire transmission satisfies this requirement much better than radio. Referring to the transcontinental line with radio extensions, which was used recently to talk from Catalina Island in the Pacific Ocean to a ship in the Atlantic Ocean, it is stated that had all of the necessary energy been introduced at one end of the circuit, there being no intermediate amplification, the total power required would have been 1.8×10^{73} kilowatts, an amount unavailable in the world. In the actual system, distributing the amplification along the transmission line, the power required sums up to something less than 1 kilowatt.

Interference between messages and extraneous disturbances is discussed, and the requirements involved in keeping message energy well above the energy level of the disturbances in both systems are pointed out. The limitations on two-way operation resulting from "singing" of the entire system are considered for both cases and for combination wire and radio circuits as well. The method of improving the efficiency of transmission by suppressing the carrier and one side band is discussed. Finally the factors involved in obtaining high grade quality of transmission are enumerated.—*Editor.*

ONE of the most interesting aspects of the development of radio during the last few years, and particularly of radio telephony, is the obvious convergence of its technique with that of wire transmission. It is, of course, the advent into both of these arts of that remarkable device, the electron tube, which is responsible for the close technical relations which now exist between them.

This community of interest, however, altho thus greatly stimulated by a device of such range of utility as to find important applications in both arts, is not due primarily to any device *per se*, but rather to the fact that both type of systems are subject fundamentally, as communication systems, to the same general requirements and design considerations concerning their intelligence-carrying capabilities. These underlying communication requirements lead to similar considerations in both types of systems as to the efficiency and fidelity with which the transmission of intelligence is effected and give rise

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to a transmission background, as it were, which is common to both arts.

The engineering handling of the transmission problems which arise from these fundamental communication requirements has been quite highly developed in the older of the two arts—wire transmission—in connection with telephone repeaters and carrier telephone and telegraph systems. It should be, therefore, interesting and profitable to apply some of the transmission technique thus developed in the wire art to several of the more important radio problems. In so doing, we obtain rather new viewpoints of radio transmission and a useful correlation of it with the better established wire methods. It is hoped, therefore, that the picture which is presented of radio and wire transmission, treated from a common standpoint, may contribute to a better appreciation of both arts by radio and wire engineers alike and may make clear the underlying transmission principles which are common to them.

Principal among the problems of electric communication is the one of delivering at the receiving end the required volume of signal with the necessary freedom from interference. The delivering of the required volume is a matter of overcoming the transmission losses of the system by amplification; while the obviating of interference is, of course, concerned with the reduction of the ratio of the interfering to the signaling energy.

Transmission Losses

In considering these factors we will take up first the primary one of the losses which are suffered by the carrier waves as they are propagated thru the transmission medium. In both wire and radio transmission, of course, the actual propagation of the electromagnetic wave energy occurs in the "ether," the difference being that in the wire case, the waves are bound to a guiding path, whereas in the radio case they are transmitted freely in all directions and bound merely to the earth's surface. This difference in the mechanism of transmission gives rise to an important difference in the transmission losses occurring in the two cases. In order to assist in visualizing the two cases they are indicated diagrammatically in Fig. 1.

Referring first to the wire case, the law in accordance with which the current and voltage strength decrease as the transmission wave travels along the wire, is the familiar one of attenuation.

$$I_1\epsilon^{-\alpha l} = I_2, \qquad (1)$$
$$E_1\epsilon^{-\alpha l} = E_2,$$

which simply expresses the fact that, as the wave proceeds along the wire, the losses in the resistance of the conductor and in the insulation, extract for each mile a certain definite proportion of the voltage and current which arrives at that point. After traveling (l) miles the original current I_1 is attenuated down to a value $I_1\epsilon^{-\alpha l}$ which represents the received current I_2. This is the same general law of damping as applies to the dying down of the voltage and current in an oscillation circuit, except that here the damping is with respect to distance along the line rather than time. We are assuming, of course, that the circuit is so terminated as to avoid reflection effects at the terminals—a condition readily met, by making the terminal impedance equal to the characteristic line impedance. This is indicated in the figure by the designations, Z (internal) equals Z (line). A similar relation is taken for the radio case. The " line " impedance is here the antenna radiation resistance while the " terminal " impedance is the resistance internal to the antenna and the apparatus, assuming resonance; thus R (internal) equals R (radiation).

WIRE AND RADIO TRANSMISSION SYSTEMS

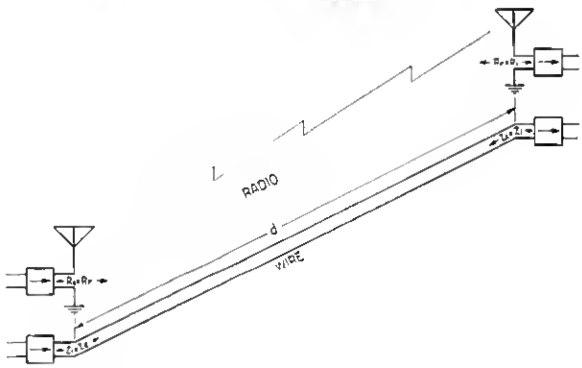

Fig. 1

We know that in radio there are two distinct causes of the transmission loss: (1) that, due to the spreading out of the waves, which is characteristic of non-guided wave transmission; and (2) that due to absorption in the air and earth's surface, which extracts a definite percentage loss for each mile of the radio circuit and which conforms, therefore, to an exponential law similar in its general nature to that of wire attenuation.

This transmission law, as expressed by the familiar Austin-Cohen

formula, is given in the Appendix.[2] In order to express the radio transmission loss in some general manner which will be comparable to the expression of wire transmission loss, these conditions have been taken for the radio case:

(1) That we will use as the measure of the transmission loss the ratio of the square root of the power radiated from the sending antenna to the square root of the power delivered in the receiving antenna. This is, of course, the same criterion as is used for wire transmission.
(2) The radiation resistance of the two antennas, sending and receiving, are made equal, analogous to the equality of line impedance at the two ends of the wire system.
(3) Also the internal antenna resistance, which corresponds to the terminating impedance in the wire case, is made equal to the radiation resistance for both ends. This is the condition of maximum power transfer between the "line" and the terminal.

These assumptions set up the two cases, radio and wire, on a comparable basis and facilitate a comparison of them. They are favorable to radio in that they do not take account of practical limitations which obtain in antennas. The radio curves should be read, therefore, as giving the minimum possible losses for daylight transmission over water.

These curves show the manner in which the transmission loss varies with distance, for various frequencies, for both radio and wire. The ordinates are plotted in terms of the logarithm of the ratio of the sent to the received currents, or voltages, in circuits of equal impedances. In so doing we are plotting the losses on the straight attenuation basis upon which they are usually plotted in the wire art; that is, the ordinates represent the exponent (αl) of the wire attenuation law, and may be directly interpreted in terms of miles of standard cable[3] by multiplying by 21. approximately. The advantage of dealing with the exponent rather than the current ratio

[2] Measurements on ship-shore transmission made since the above was written, indicate that the Austin-Cohen law holds quite well for frequencies as high as about 1,000,000 cycles.

[3] For the mile of standard cable the attenuation α (at 800 cycles) equals 0.109. Therefore the equation for current ratio, in terms of miles of standard cable, becomes

$$\frac{I_1}{I_2} = \epsilon^{\alpha l} = \epsilon^{0.109 l}$$

from which

$$l = \frac{1}{0.109} \log_\epsilon \frac{I_1}{I_2} = 21.13 \log_{10} \frac{I_1}{I_2}.$$

itself is the very considerable one which is characteristic of logarithms, namely, that when thus expressed the individual losses and gains thruout a system may be summed up algebraically, and the over-all transmission equivalent of the system thus readily determined.

It should be noted that the transmission loss given in the radio curves is that obtaining between the point at which power is delivered to the ether at the sending end and that at which it is delivered to the dissipative load of the receiving antenna circuit. In Fig. 1 these points are represented by R_r at the transmitter and R_i at the receiver. If at the sending end, we start with the power developed within the generator, meaning in R_i instead of R_r, then the power ratio is simply doubled, for the conditions assumed, and the attenuation is 0.15 units or about 3 miles greater than given in the curves. The curves can be used for obtaining the loss in any practical case simply by taking the minimum loss as given by the curves and adding thereto the additional loss obtaining in the actual antenna.

Referring now to Fig. 2—the transmission losses in the two cases are given for distances up to 200 miles (320 km.). The straight lines represent the wire losses, the bending-over curves the radio losses. Of the radio curves, the dash lines give the spreading-out losses alone, while the full lines give the total losses, including absorption.

The first thing one observes is the difference in the nature of the two sets of curves—the wire losses being represented by straight lines, because of their exponential law and the fact that it is the logarithm or the exponent itself which is being plotted, while the radio curves jump up rapidly at first and then straighten out, in accordance with the " inverse-with-distance " law.

The second thing one notes is the fact that as a result of the large initial (or " jump off ") loss, the radio values run on the whole higher than do the wire for the more usable wire frequencies, and very much greater than the wire losses at telephone frequencies (1 k.c.).[4] For the wire case the number 8 Birmingham wire gauge open wire circuit is taken.[5] This is the standard long distance telephone circuit of the United States. The constants are given in the appendix.

A third characteristic which one notes in the radio curves is that the losses are greater for the higher frequencies or, conversely, lower for the lower frequencies. This is because the efficiency of the antenna has been kept constant for all frequencies. In practice the

[4] 1 k.c. is 1 kilocycle per second or 1,000 cycles per second.

[5] Diameter of number 8 Birmingham wire gauge wire = 0.165 in. = 0.42 cm.

transmission losses at the lower frequencies are higher than here indicated because of limitations in antenna heights.

Were we to take the ideal condition *as regards the transmission medium itself*, where for wires there is no conductor or dielectric loss, and for radio there is, likewise, no earth or air absorption loss, we would note: (1) that, for wires, there would be no attenuation what-

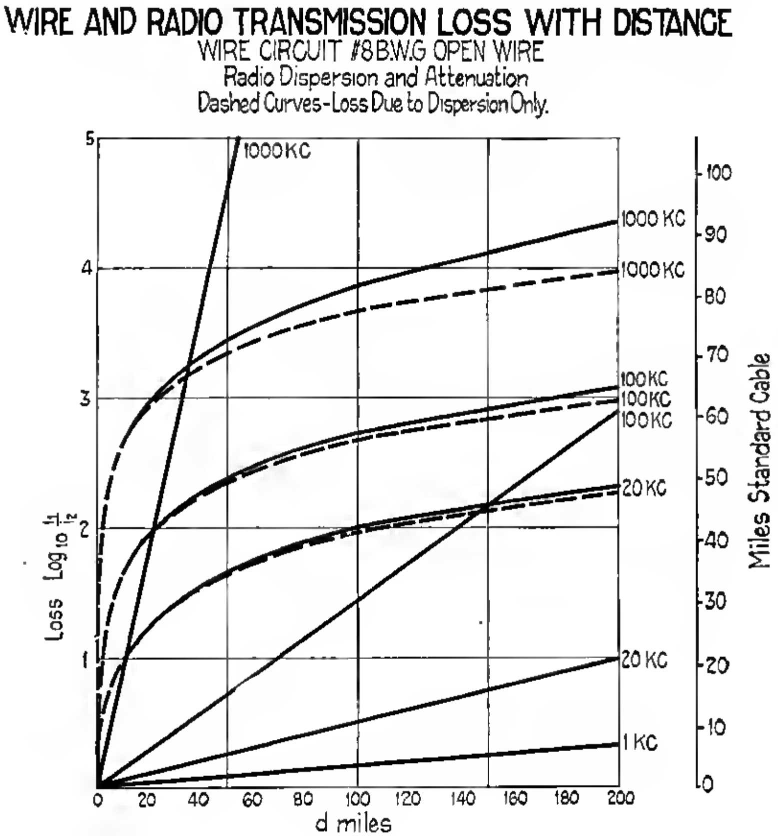

Fig. 2

ever, the curve following along the X axis; (2) for radio, there would remain the loss due to dispersion, inherent in the unguided method of transmission, the magnitude of which loss is, of course, very substantial. The dash-line radio curves show the radio losses without attenuation, the full line curves with attenuation.

Considering the actual condition, where there is dissipative loss

in the transmitting medium, we find that for moderate distances, up to 200 miles (320 km.), as plotted in Fig. 2, the wire losses are in general less, and at telephone frequencies very much less, than the radio losses. The low wire attenuation at telephone frequencies is, of course, in keeping with experience and accounts for the economical terminal apparatus which is employed in telephone practice. Likewise the relatively high losses for radio accounts for the large amplification at either the sending or receiving end or both, which experience has proven to be necessary. This brings in an interesting side-

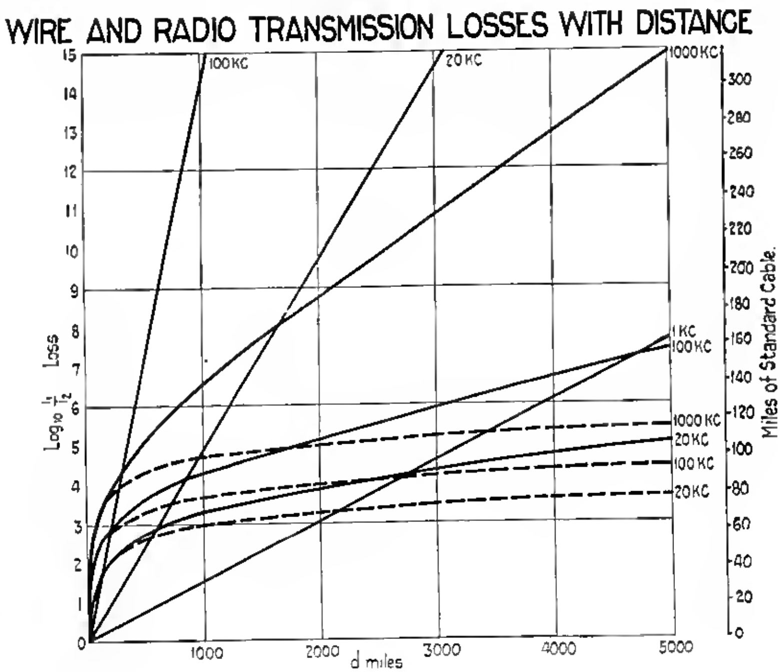

Fig. 3

light, namely, that altho in radio the transmission medium is provided by nature, the effective *use* of this medium is not as economical as might be expected because it requires considerable equipment, amplifiers at both ends for overcoming the large attenuations, selective means for dividing-up the frequency range and thereby "multiplexing" the ether, and antennas for getting into the medium and out again.

For the higher frequencies, the wire attenuations increase relatively more rapidly than the radio, thus limiting the frequency range

which can be employed on wires without likewise running into large amplification requirements. For example, the loss at 100,000 cycles for a distance of 200 miles (320 km.) is about as great over wires as the minimum loss which it is theoretically possible to obtain over radio.

Referring now to the attenuations for longer distances, as given in Fig. 3, it is of interest to note that for distances of the order of 2,000 to 3,000 miles (3,200 to 4,800 km.) the lower radio frequency curves cross the 1,000 cycle wire curve, meaning that for these distances it is possible for radio transmission to be as efficient as straight telephone transmission. The wires present to carrier frequencies for these long distances losses which are generally greater than prevail for radio.

These attenuation relations cannot be directly converted into an economic comparison, however, for the economies depend not upon the attenuation itself but upon, among other factors, the cost involved in *overcoming* the losses by means of amplification; and this cost in turn depends largely upon the extent to which the amplification can be applied at weak powers, as by the frequent application of telephone repeaters. By applying repeaters every few hundred miles in the wire case, the attenuation is prevented from piling up and the amplification is handled at relatively weak and therefore economical power levels. This brings us to the point of requiring that the attenuation values given above, be considered in reference to the amplification and power required to overcome them and yield the necessary volume of transmission at the receiving end over and above interference.

Interference and Its Effect Upon the Transmitting Power Required

In both the radio and wire cases there is always present in the transmission medium a certain amount of stray wave energy which tends to interfere with the proper reception of the message-carrying waves. It is necessary that the communication waves arrive at the receiving end of the system with such power as to be large compared with the interfering waves—by a factor determined by the type and grade of communication involved. Inasmuch as the stray energy always has some finite value, this requirement of freedom from interference will determine in the radio case as well as in some types of wire transmission the minimum wave power required at the receiving end of the transmission system.

In the wire system the minumum power requirement may be expressed directly in terms of a power, or—as it is usually—a current, in the receiving apparatus, the "transfer" between the line and the receiver being a constant and efficient relation. In radio the power delivered out of the ether or "line" into the receiving antenna is so

RADIO TRANSMISSION LEVEL DIAGAM

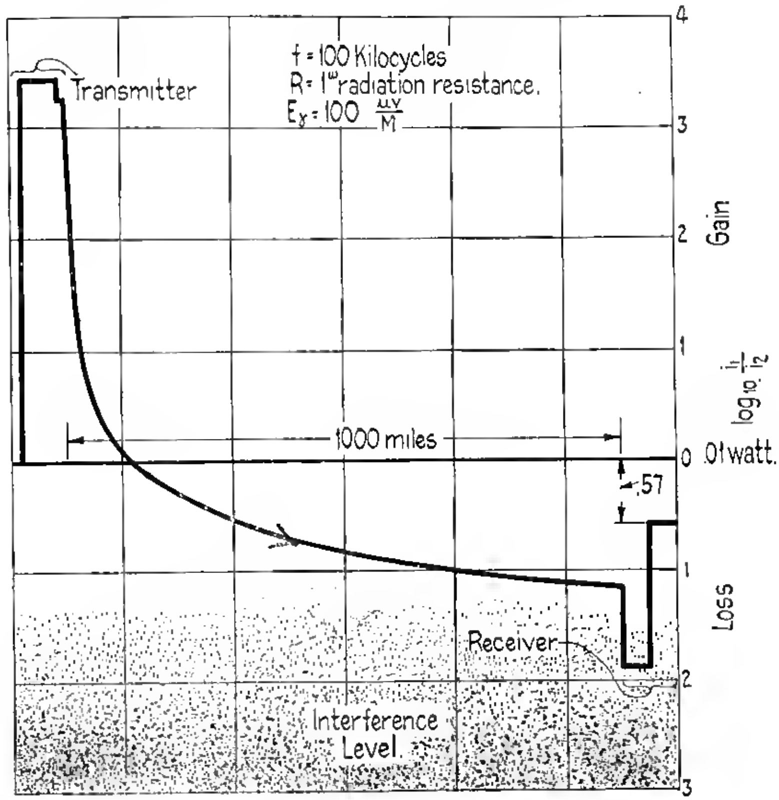

Fig. 4

largely a function of the antenna dimensions that it is necessary to express the necessary received power in terms of the received field, usually, simply as a field intensity—and not as a certain current in the terminal apparatus. Of course, the transmission loss occasioned by getting from the "ether" into the receiving circuit does not affect

the interference relation but merely the absolute amount of terminal amplification required. On the other hand the transmission loss occasioned by getting into the "ether" at the sending end affects the interference relation vitally, as we shall see.

Transmission Levels

This necessity of having to keep the power of the received waves above the interference level may be visualized by reference to Fig. 4. Here we have what in wire practice is called a "transmission level" diagram. Such a diagram is useful in showing what goes on in the system from the power and interference standpoints. The vertical scale is plotted in terms of the transmission level expressed as the logarithm of the current or field intensity ratios, and the horizontal scale represents progression along the system. For illustration purposes, the presence of interference is indicated at the bottom of the transmission-level scale by the shading.

Tracing thru the diagram we proceed as follows:

The point of "zero"level is taken roughly as that corresponding to the power delivered into a telephone circuit by a certain telephone transmitter when spoken into by the average talker, and is here taken to be 0.01 watt. As the voice currents are amplified to power proportions in the transmitting station, at the left, the transmission level is greatly increased, as illustrated by the vertical jump in the curve. The amplified voice currents are assumed to be converted by modulation into high frequency currents at this high power level and put into the antenna. The high frequency loss in the antenna system is indicated by the perpendicular jog in the curve. The drooping-off curve then commences, starting with a point which represents the power usefully applied to the ether in accordance with the expression I^2R, where I is the antenna current and R is the radiation resistance. The level curve falls off in accordance with the transmission loss curves previously discussed, as it extends across the transmitting medium to the receiving station. It will not do to permit the transmission level to fall as low as that of the interference, so I have shown that the transmission reaches the receiving station before dropping down very far into the interference level. At the receiving point a further transmission loss occurs in getting into the receiving antenna circuit, shown by the drop in the curve, but this loss obtains for the interference as well as the desired signals and does not affect the interference ratio. The terminal amplification brings the level up to that required for suitable audition and the difference between

where this level leaves off and the original zero level, measures the over-all transmission equivalent of the circuit, shown in this case as about $\log_{10} \frac{I_1}{I_2} = 0.57$ or about 12 miles of standard cable. This corresponds to a current ratio of about 4, a value ample for good " talk." Of course, in a one-way circuit the terminal amplification can be raised to any value desired. In a two-way circuit, however, a limit in the terminal amplification is imposed by interference between the two transmissions, as will be understood subsequently.

We may make the following useful observations from this curve:

1. The net transmission equivalent represents the difference between the over-all loss and the over-all gain.
2. The over-all gain is divided between the transmitting and receiving ends. We should like to throw as much of this amplification as possible to the receiving end because of the economy with which amplification can be provided at low powers.
3. The extent to which we can do this, however, is distinctly limited by the fact that the transmission level obtaining at the receiving end in the transmission medium must be held above a certain amount in order to overcome interference.
4. It is, then, the absolute intensity of the interference which determines the receiving power level required, and in turn this together with the attenuation back to the transmitting station which determines the transmitting power required.

Thus the two transmission features most fundamentally important in a radio communication system are (1) the interference level and (2) the transmission loss thru the medium. These once given, the other engineering considerations follow naturally. There are analogously fundamental factors in wire communication systems. In the latter case, however, the art has advanced to a point where means of controlling the interference level are available, so that the ratio of interference to transmitted power may be made small by decreasing the former rather than increasing the latter.

Minimum Transmission Levels Obtaining in Practice

The working value which should be assumed for the ratio between the transmission level of the received signals and the interference, depend upon the type of communication involved, whether it is telephone or telegraph, for example, and upon the grade of service to be given. There is a wide difference between the transmission level which will enable telephonic signals to be barely discerned by an

expert ear and that which is required for a public service communication system which must provide sufficient operating margin to enable the average person to converse with ease and certainty under all ordinary conditions. Under favorable static conditions, the transmission level can be permitted to fall to extraordinarily low values. When this condition is accompanied by a substantial reduction in the effective attenuation, which sometimes occurs at short wave lengths especially at night, apparently due to the effective absence of either absorption, then it becomes possible to "get thru" over relatively long distances with powers diminutive as compared with those required for giving a regular service. With these exceptional transmission conditions we are, of course, familiar. They are exemplified by the long distances reached at night by the amateurs, as across the Atlantic, and by the hearing of the normally 30-mile (48 km.) Catalina Island system in Australian waters. The transmission curves of Fig. 3 account for these unusual long distance transmissions if we assume that the attenuation due to absorption is eliminated on these occasions by some natural cause. Thus, at 3,000 miles (4,800 km.) the curves for 1,000 kilocycles (300 meters), for example, show that were the absorption eliminated, the transmission equivalent would be improved by the difference between about 10.8 and 5.2 for $\log_{10} \frac{I_1}{I_2}$, or 5.6, an improvement equivalent to a little over 100 miles of standard cable. The remaining or purely spreading-out loss of about 5 units, or 100 miles of standard cable, is then taken care of by the sending and receiving amplification.

Interference may occur in either or both of two ways—by the interference level rising to a point comparable with the normal transmission level at the receiving end of the ether circuit, or by the transmission level of the waves themselves dropping so low, due to excessive atmospheric absorption, as to fall below that of the atmospheric disturbances. For reliable transmission it is necessary, therefore, to deliver normally at the receiving end, a wave intensity sufficient to allow for the fluctuations which occur in atmospheric absorption and in the intensity level of the atmospherics. The importance of working to transmission level standards which give an adequate operating margin against interference, for the types of service required, will be appreciated from the foregoing. The following values of minimum transmission levels will be of value to know:

(a) For carrier wire telephone transmission at frequencies in the tens of thousandths of cycles, the limiting interference may be

our old friend "static" or some interference is experienced from high frequency transients in power systems. Unless the lines are especially well transposed for these frequencies, the interference requires that the transmission level be kept above a minimum value of the order of $\log_{10} \frac{I_1}{I_2} = 1.2$ (about -25 miles of standard cable below zero level).

(b) While for radio telephone transmission the available data are as yet very meagre, we have obtained a few order-of-magnitude figures which should be of interest. For the Catalina Island radiophone system, for example, the minimum field intensity is estimated at roughly 1,000 microvolts per meter. The circuit is sometimes quite noisy during the summer months altho not prohibitively so. In our ship-to-shore radio telephone experiments along the Atlantic coast, we have on occasions worked with lower field intensities, as low as 100 microvolts per meter. The latter figure, however, gives a grade of service far below wire standards.

(c) The best data on the minimum permissible transmission level for radio telegraphy are those obtained from the experience in trans-Atlantic telegraph operation. The figures prevailing for present trans-oceanic radio-telegraph operation are understood to lie in the order of 10 to 100 microvolts per meter, depending upon individual cases and the time of the year.

The Net Transmission Equivalent

The net over-all transmission equivalent of the system is measured by the ratio of the transmitted to the received signaling power, and is shown in Fig. 4 as the difference between the transmission levels at the two ends. This relatively small loss represents the difference between two large values, the transmission loss and the transmission gain thruout the system. Relatively small changes in either the attenuation or amplification may, therefore, cause large changes in the net equivalent of the circuit, thus tending to give rise to instability in the transmission performance of the circuit.

This problem of fluctuation becomes very serious with the use of very high frequencies, whether transmitted by wires or by radio. Were we to attempt to employ, for example, a million cycles for wire carrier transmission over considerable distances, as has been proposed, not only would the losses be very large, but they would be unstable, changing with weather conditions, so that the maintenance of a

constant volume of transmission would become extremely difficult. Similarly in radio transmission, the fluctuations in the ether attenuation, particularly at short wave lengths where over long distances we experience the well known "swinging" or fading effects, render the maintenance of a satisfactory volume of transmission a difficult problem. As noted above these fluctuations, particularly as between day and night transmission with very high frequencies, may be enormous.

It is of value to the radio engineer to have some idea of the over-all circuit transmission equivalents which are necessary for satisfactory telephone communication. In the wire telephone art, the maximum equivalent between subscribers is ordinarily taken as about 30 miles of standard cable or $\log_{10} \frac{I_1}{I_2} = 1.4$. Under quiet conditions, considerably larger transmission equivalents can be talked over. The long distance toll lines themselves are usually designed for transmission equivalents of 0.5 to 0.75 or 10 to 15 miles of standard cable. These figures will serve as a general guide for the transmission equivalents which radio telephone circuits should provide. Where a radio circuit forms a link in a direct wire circuit as, for example, in the case of Catalina Island, it is desirable to work the radio link as close to a zero equivalent as possible, that is, to give out at the receiving end a volume nearly equal to that fed in at the transmitting end.

Two-Way Operation

When the two one-way radio channels are merged at their two ends into a regular telephone circuit for connection to the wire network, as illustrated in Fig. 5, then there is a limit in the transmission equivalent which can be given over the radio part of the circuit.

This limit will be appreciated by reference to Fig. 5. It is imposed by the tendency of the two one-way channels to form a round-trip circuit by "feeding-back" from one to the other via the voice frequency connecting circuit. If the total amplification around the circuit including the voice-frequency line, exceeds the total losses in the circuit, "singing" will result. Were no line balance provided at the voice frequency terminals, then it would be impossible to operate the circuit at a zero equivalent. By setting up a balancing circuit at each end in the manner illustrated, a transmission loss is, in effect, inserted between the sending and receiving sides of the voice circuit which tends to prevent this sing-around action. Actually, there is a limitation in the degree of balance which can be realized between the

telephone line and the balancing network, especially if the telephone line is to be switched at a nearby central office, and this factor, together with the margin of safety which is required between the operating condition and the singing condition, prevents the radio channels from being operated much better than the zero equivalent. This whole matter of realizing in practice an adequate transmission equivalent, will be appreciated to be an especially difficult problem in the case of marine radio telephony, where the connection is switched from one vessel to another at varying distances.

It should be noted further, with reference to two-way operation, that the difficulty of effecting simultaneous sending and receiving at a station arises primarily from the large attenuation which must be

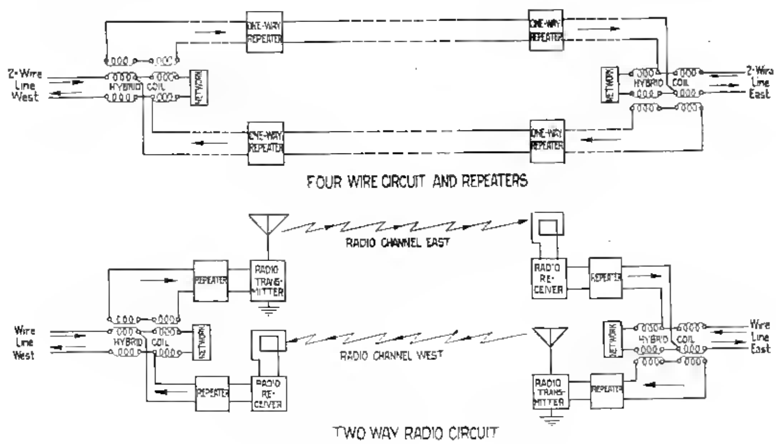

Fig. 5

overcome and the resulting large ratio between the energies transmitted into and received from the ether. The receiver must be prevented from being overloaded by the home transmitter and this, in general, requires that there be provided between the high frequency side of the transmitter and that of the receiver, a transmission loss comparable in size to that obtaining over the radio circuit itself. This "separating" transmission loss is ordinarily provided (a) by frequency-selecting circuits (tuned circuits and filters), the sending and receiving transmissions being placed on different frequencies; (b) by balance, as when using the blind spot of a loop-antenna receiver, and (c) by spatial separation between sending and receiving points, where the large step-off loss is used to advantage.

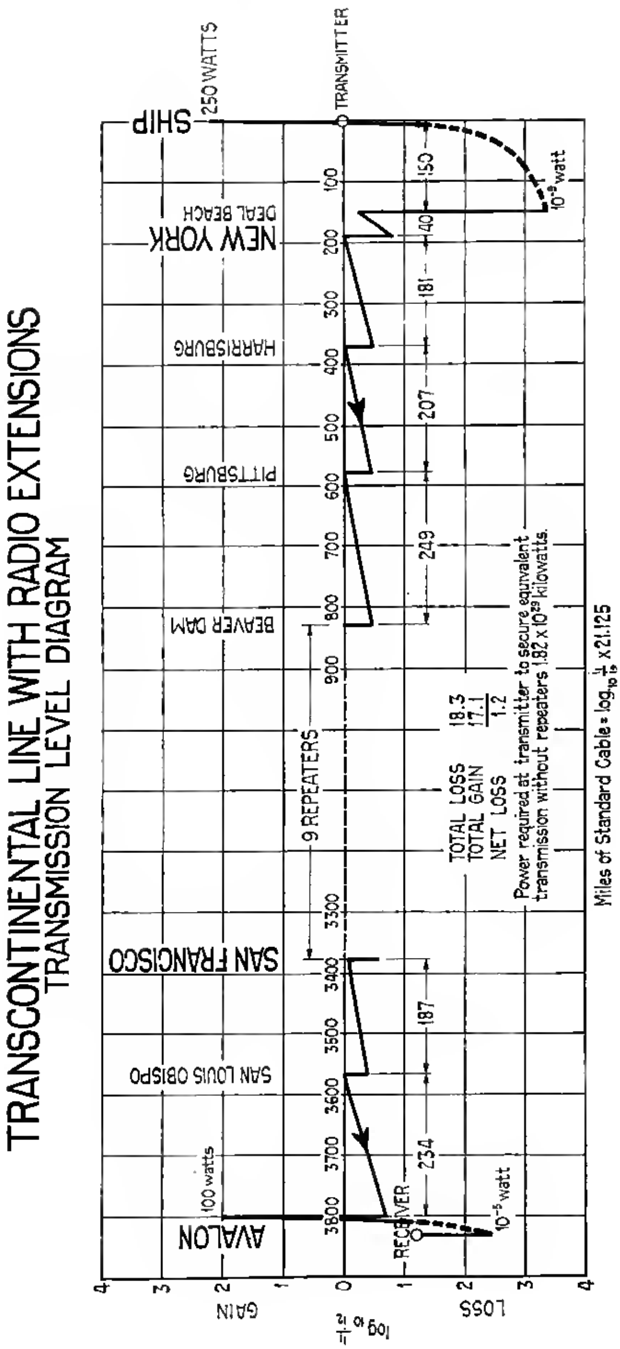
TRANSCONTINENTAL LINE WITH RADIO EXTENSIONS
TRANSMISSION LEVEL DIAGRAM
SHIP
250 WATTS
TRANSMITTER
NEW YORK
DEAL BEACH
HARRISBURG
PITTSBURG
BEAVER DAM
9 REPEATERS
SAN FRANCISCO
SAN LUIS OBISPO
AVALON
100 watts
RECEIVER
10^{-5} watt
10^{-8} watt
TOTAL LOSS 18.3
TOTAL GAIN 17.1
NET LOSS 1.2
Power required at transmitter to secure equivalent transmission without repeaters 1.82×10^{29} kilowatts.
Miles of Standard Cable = $\log_{10}\frac{I_1}{I_2} \times 21.125$
GAIN
LOSS
$\log_{10}\frac{I_1}{I_2}$

Fig. 6

Transmission Levels on Combination Wire and Radio Telephone Systems

It will be of interest to trace thru the approximate transmission levels which obtain for a radio system linked up with a long repeatered land line system.

In Fig. 6, there is taken a rather striking example of this case in the transcontinental telephone line as connected up to radio extensions at its termini—to Catalina Island on the Pacific and to a vessel at sea on the Atlantic. The transmission illustrated is that occurring from east to west. The voice currents start out from the vessel at zero level, are amplified to a relatively high level and upon being transmitted to the shore 150 miles (240 km.) away, drop to a very low level. At the shore radio station they are boosted up, at New York amplified again, and put upon the transcontinental circuit. Regularly at about 300 miles (480 km.) the telephone repeaters pull back the transmission level to about its original value. In the radio link at the western end the currents are again amplified to a high level at the transmitting station, drop down to a very low level at the receiver and are brought back to a level at which they can be heard. Actually in the receiving telephone the transmission is about $\log_{10} \frac{I_1}{I_2} = 1.2$ below zero level, or roughly 25 miles of standard cable "down." The total loss and the total gain in the circuit is enormous, as is shown by the figures given in the diagram. This is a rather striking illustration of the extent to which amplification properly distributed and maintained can be used to overcome attenuations enormous in the aggregate. Just to give a better idea of what these values of attenuation and amplification mean, it may be noted that were it necessary to supply at the transmitting end all of the amplification required for delivering this volume of transmission to the receiving end thru the combination circuit, the kilowatts required would be measured by a twenty-nine place figure, an amount of power unavailable in the world. The importance of correctly distributing the amplification along the system is well illustrated by this figure by comparing it with the signaling power actually represented in the system, which sums up to something less than 1 kilowatt. The difference is simply a question of the transmission level at which the amplification is worked.

Fig. 7 gives a view of the interior of one of these radio telephone stations of the American Telephone and Telegraph Company and Western Electric Company. It is located at Deal Beach, New Jersey.

In the foreground is the switchboard for enabling the operator to control the radio-wire circuit at the connecting point. In the background are the transmitter units—four of them. These, together with the four antennas with which the station is equipped, "multiplex" the ether, in effect, and permit four channels to be established to as many distant stations. It is intended that three of these be telephone talking channels and the fourth a signaling or a reserve talking channel. The receiving station is located at another point. It is not desired to describe this station in any detail but merely to illustrate it as an example of a radio repeating station functioning to

Fig. 7

connect the wire system with ships at sea and capable of effecting simultaneously three different connections. It is hoped that this ship-to-shore development may be itself the subject of an *Institute* paper.

Intermediate Repeaters

The transcontinental line with radio extensions as shown in Fig. 6 is a good illustration of the use of intermediate repeaters generally. Two types of repeaters are represented, the straight wire telephone

repeaters and the shore radio stations which are in effect huge repeaters relaying between the land line and the radio circuits.

Because of the moderate attenuation obtaining in the wire transmission system, we can work with fairly long repeater spacings, about 300 miles in this case, and with moderate amounts of power and yet keep the transmission levels at the receiving end relatively much

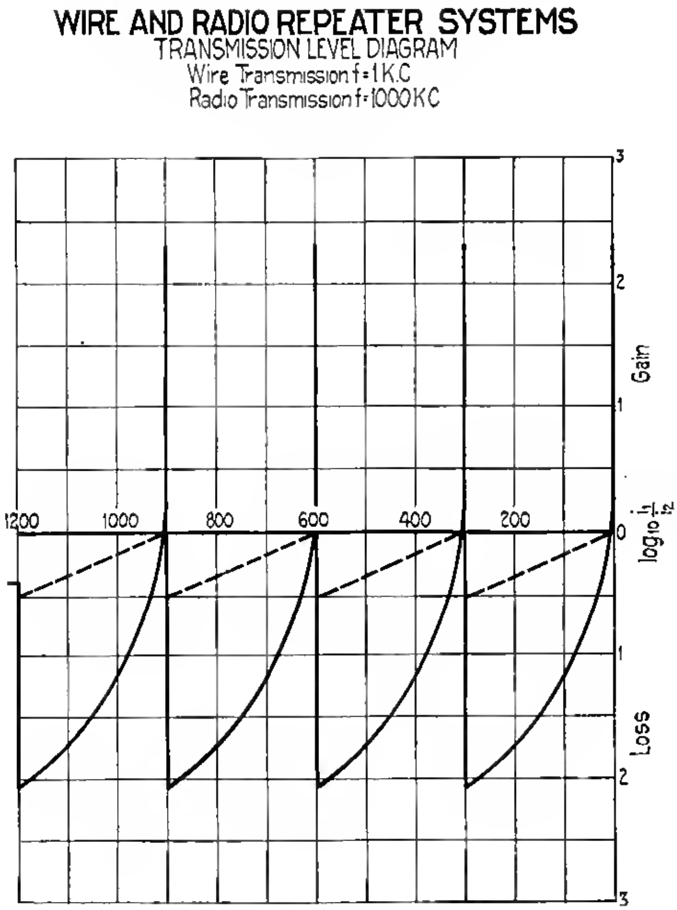

Fig. 8

higher than is usual in radio systems. Due to the large attenuations obtaining over the radio extensions, the radio repeaters must put out a high transmission level, making them costly, and even with this relatively high output, the level drops to very low values at the receiving

end. This falling off occurs largely in the get-away loss at the transmitting end of the radio circuit, as the diagram indicates.

Fig. 8 depicts an all-radio system provided with intermediate repeaters and compares for illustration purposes the transmission levels obtaining therein with those for a wire system. The solid lines are for radio and the dash for wire. It will be seen that the radio system courses thru wide transmission level variations as compared to the ordinary wire system due to the large attenuations obtaining and particularly to the large step-off loss near the sending station.

The figure illustrates the same spacing for both radio and wire repeating and gives a measure of the difference in amplification required in the two cases. Altho in the radio repeaters the level can be permitted to drop to low values, nevertheless a large part of the total amplification has to be supplied at relatively high power levels and it is this fact, together with the antenna structures required at each point to "get into" the ether transmission medium anew, that militates against the economics of radio repeaters as compared with straight-away radio transmission. The tendency will be to "stretch out" the straight-away transmission due to the fact that for the longer distances the transmission loss increases relatively slowly. While we may look for some important uses of radio repeaters in special cases, we should not, in general, expect them to be as important to the radio art as are wire repeaters in wire operation.

Transmission of Side Band Without Carrier

In dealing with the subject of power levels in radio transmission, it is important to recognize that a modulated radio telephone wave consists of two components, one, the carrier frequency itself and the other, the so-called side bands, which are the actual modulated components. This resolution of the modulated carrier into two or, rather, three components, the carrier and two side-bands, has been given mathematically a number of times and need not be repeated. It is physically analogous to the resolution of the unidirectional current of a microphone transmitter into direct current and alternating current components, the direct current corresponding to the carrier and the alternating current to the modulated components.

Now, the important thing about this matter of side bands and the unmodulated carrier component, with reference to transmission considerations, is this, that it is the side bands alone, and not the carrier, which convey the actual intelligence. The function of the

carrier comes in merely at the receiving end, in the detector, as a means for translating the side band from radio frequency back to audio frequency.

This will be made clearer by reference to Fig. 9. At the bottom of the figure is shown schematically a one-way radio system. Above it is depicted the voice-frequency band, showing the manner in which it is shifted by modulation up to the carrier frequency range, and at the receiving end, by detection, back to the voice frequency range. The voice frequency band, as it comes out of the ordinary telephone transmitter, is shown at (b_1) at its normal telephone-frequency posi-

RADIO TRANSMISSION WITH CARRIER AND SIDE BAND SUPPRESSION

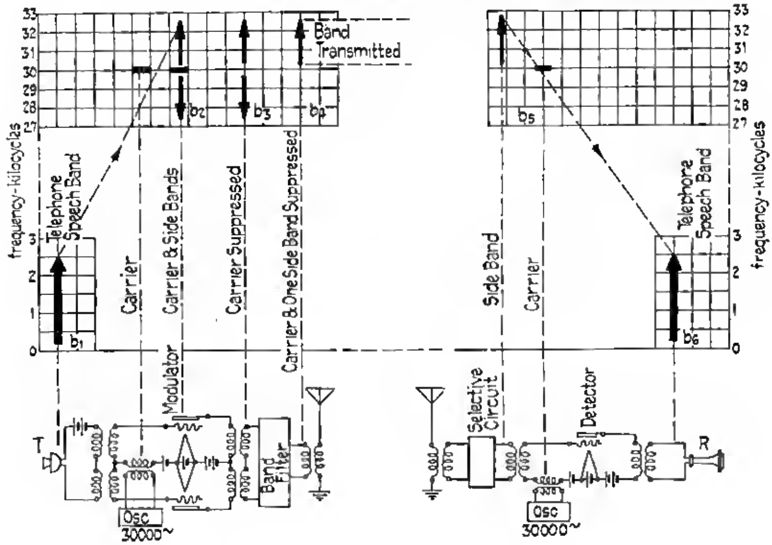

Fig. 9

tion. Upon modulation with the carrier the reference point of the voice frequency band is shifted from zero frequency (direct current) up to the carrier frequency as shown at b_2 where the two side bands appear. The effect of modulation is, therefore, simply to shift the band of signaling frequencies upward in the frequency range and refer it in a double relation to the carrier frequency.

Located between the upper and lower side band in the figure, there is indicated the unmodulated component of the carrier. The fact that this component is unnecessary so far as the actual intelligence-carrying energy is concerned, is proven by the fact that it need not be transmitted to the receiver. The carrier may be sup-

pressed as shown at b_3. A means for doing this is the Carson balanced tube modulator circuit illustrated below in the figure.

A reduction of the total band can be effected by filtering out one of them as shown at b_4. The remaining single band is the simplest component of the modulation process with which intelligence can be transmitted to the distant end. Upon arriving at the receiving end at b_5, this side band is fed into the detector along with a carrier of the same frequency as that employed at the sending end; these two components demodulate one another, with the result that the side band is shifted down to its original audio-frequency position in the scale, as indicated at b_6.

Actually this general method of transmission, involving both carrier suppression and side band elimination, is being employed in wire carrier systems in the Bell Telephone Plant.[6] It is briefly explained here because it represents a valuable improvement in wire transmission which should have important application in radio.

From the standpoint of transmission levels its application is in showing that the real intelligence-carrying component of a radio wave is the side-band and not the carrier itself. In considering transmission levels accurately care should be taken, therefore, to deal in terms of the level or wave-intensity of the side-band component and not the carrier. It is because of this that as nearly complete modulation as possible is desired at the transmitting station.

It follows that the power resident in the carrier is a pure waste in so far as overcoming interference is concerned. An important power saving can be effected in the transmitting station by providing some such means as is illustrated whereby the carrier power is held back in the circuit. The two side-bands together can never be greater in current and voltage value than the carrier, and each side-band alone cannot be greater than half the carrier. The power of the carrier is therefore always at least four times the power of one side-band or twice that of both together. Thus by " holding-back " the carrier at the transmitter we can transmit with but one-third the power ordinarily required. Actually the power saving is much greater than this because of the necessity of normally working with larger ratios between carrier and side-band in order to accommodate the peaks of the telephone waves and thereby preserve the quality of transmission. The power saving is, of course, especially important in long distance work.

The suppression of one of the two side-bands halves the frequency

[6] "Carrier Current Telephony and Telegraphy," by Colpitts and Blackwell, *Journal of the American Institute of Electrical Engineers*, February 16–18, 1921.

band required for transmission and would double the message-carrying capacity of the ether were no frequency range required to space the channels apart. This advantage of the present method is likewise of special importance in long-distance-long-wave transmission.

Quality of Transmission

We have spoken above of factors concerned with the volume of transmission and only incidentally of that other requisite of transmission, namely, good quality. Without going into this matter in much detail, it will be well to make note of the several factors involved in obtaining good quality, as follows:

1. It is important that a substantial *band* of voice frequencies be transmitted. Of course, distorted talk can be transmitted on a relatively narrow band, but commercial transmission has been found to require a single side-band width of the order of 2,000 or more cycles, the band width increasing with the quality desired, up to about 5,000 cycles.

2. It is necessary that the distortion which is due to non-linearity of transmission with respect to amplitude, be avoided. This is equivalent to saying that there should not be permitted to take place self-modulation between the components of the side-band, nor the too close cutting-off of the peaks of the telephone waves due to saturation effects.

3. The transmission must be kept free from interfering noises. The ratio between interfering noise current and voice currents of the order of 0.1 is regarded as large in wire practice. While this amount of interfering current will not prohibit service, it does seriously impair the effectiveness of transmission and annoys the listener. In radio the ratio of static noise to signal strength is very often much greater than this value. As the radio art progresses it will be necessary to work toward standards more nearly in keeping with those which have been found necessary for wire service.

The writer wishes to express his indebtedness to the following of his associates for helpful suggestions and assistance—Messrs. J. R. Carson, Ralph Bown, and D. K. Martin.

APPENDIX

The curves of Figs. 2 and 3 are based upon the following equations and data:

The radio curves are based on the familiar Austin-Cohen formula:

$$I = \frac{7.8 \times 10^{-10}\, h_r\, h_s\, f\, I_s}{R\, d}\, \epsilon^{-4.4 \times 10^{-6} d \sqrt{f}} \tag{1}$$

where I = amperes
R = ohms
h = meters
f = cycles
d = miles

Taking equal antenna heights at two ends $h_s = h_r$.

As regards antenna resistance we assume symmetry as between the two ends, and that the external (radiation) resistance of the antenna equals the resistance within the antenna (which resistance would be internal apparatus resistance in the case of a perfect antenna). This makes R_r (radiation resistance) $= R_i$ (ohmic resistance); and R of (1) becomes $= R_r + R_i$ where:

$$R_r = 17.8 \times 10^{-15}\, h^2 f^2. \tag{2}$$

Expressing in terms of current ratio and substituting values of R, equation (1) becomes,

$$\frac{I_s}{I_r} = 45.5 \times 10^{-6} f\, d.\ \ \epsilon^{4.4 \times 10^{-6} d \sqrt{f}}. \tag{3}$$

In order to plot this equation on the same basis as we usually plot wire attenuation, the logarithm of the ratio is used, thus;

$$\log_{10} \frac{I_s}{I_r} = \log_{10} 45.5 \times 10^{-6} f\, d + \frac{4.4 \times 10^{-6}}{2.303}\, d \sqrt{f} \tag{4}$$

which is the equation of the curves plotted.

The ratio of the currents in the two antennas is in this case a true measure of the transmission because they are in circuits of equal impedances, by the assumption of antenna symmetry.

Data for the Wire Curves

$$\alpha = \frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}}.$$

For number 8 Birmingham wire gauge open wire (diam. = 0.165 in. = 4.19mm. wire spacing = 12 in. = 30.5 cm. 40 poles per mile) dry weather, the constants per mile are;

$$L = 3{,}370\ \mu h.$$
$$C = 9{,}140\ \mu\mu f.$$

	Frequency, Kilocycles				
	1	20	100	1000	
$R =$	0.14	10.0	21.5	65.7	ohms per loop mile
$G =$	0.55	10.0	*50.0	*500.0	μ ohms per loop mile
$\alpha =$	0.003488	0.0112	0.03289	0.2059	

* Estimated.